

Towards extracting the best possible results from NO ν A

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Abstract

The NuMI Off-Axis ν_e Appearance (NO ν A) is the currently running leading long-baseline neutrino oscillation experiment, whose main physics goal is to explore the current issues in the neutrino sector, such as determination of the neutrino mass ordering, resolution of the octant of atmospheric mixing angle and to constrain the Dirac-type CP violating phase δ_{CP} . In this paper, we would like to investigate whether it is possible to extract the best possible results from NO ν A with a shorter time-span than its scheduled run period by analyzing its capability to discriminate the degeneracy among various neutrino oscillation parameters within four years of run time, with two years in each neutrino and antineutrino modes. Further, we study the same by adding the data from T2K experiment for a total of five years run with 3.5 years in neutrino mode and 1.5 years in antineutrino mode. We find that NO ν A (2+2) has a better oscillation parameter degeneracy discrimination capability compared to its scheduled run period for four years, i.e, NO ν A (3+1).

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I. INTRODUCTION

The results from various neutrino oscillation experiments [1–8] confirm that neutrino flavours mix with each other and neutrinos do possess tiny but non-zero masses. This mixing of neutrino can be described by a unitary matrix, so called Pontecorvo-Maki-Nagakawa-Sakata (PMNS) matrix, which is parameterized by three mixing angles, often referred to as the solar mixing angle (θ_{12}), atmospheric mixing angle (θ_{23}), reactor mixing angle (θ_{13}) and a Dirac-type CP violating phase (δ_{CP}) [9, 10]. The probability of neutrino oscillation depends on these parameters as well as on two mass squared differences namely, the solar mass squared difference (Δm_{21}^2) and the atmospheric mass squared difference (Δm_{31}^2). All these parameters are determined through various neutrino experiments except the Dirac CP phase. However, we do not know the mass ordering of neutrinos, i.e, the sign of Δm_{31}^2 and this left us with two choices like normal ordering/hierarchy (NH) with $\Delta m_{31}^2 > 0$ and inverted ordering/hierarchy with $\Delta m_{31}^2 < 0$. Furthermore, recent experimental result from MINOS [11] shows that θ_{23} is non-maximal. Therefore, the octant of the mixing angle θ_{23} remains unknown, i.e, whether it lies in lower octant (LO) i.e., $\theta_{23} < 45^\circ$ or in higher octant (HO) with $\theta_{23} > 45^\circ$. There are many neutrino oscillation experiments which are intended to determine these unknowns. Among all these experiments, NO ν A is one of the new generation accelerator based long-baseline experiment which aims to determine most of these unknown parameters.

NO ν A [12] experiment is currently running long-baseline neutrino oscillation experiment, which uses an upgraded NuMI beam power of 0.7 MW at Fermilab. It has a 14 kton totally active scintillator detector (TASD) placed 0.8° off-axis from the NuMI beam near the Ash River, situated 810 km far away from Fermilab. It also has a 0.3 kton near detector located at the Fermilab site to monitor the un-oscillated neutrino or anti-neutrino flux. This experiment is designed to observe both $\nu_e(\bar{\nu}_e)$ appearance events and $\nu_\mu(\bar{\nu}_\mu)$ disappearance events. The main physics goals of this experiment are

- Appearance events: To determine the value of θ_{13} , determination of the octant of θ_{23} , mass ordering and constrain the Dirac CP phase.
- Disappearance events: The precision measurement of atmospheric oscillation parameters, Δm_{23}^2 and θ_{23} .

The determination of these parameters by an oscillation experiment like NO ν A, which is mainly rely on the oscillation probability, is extremely difficult due to the parameter degeneracies, since various combination of these parameters give the same probability. A lot of work has been done in the literature to resolve these degeneracies among oscillation parameters [13–15]. Moreover, there was a suggestion for the need of an early anti-neutrino run to get a first hint of mass ordering in NO ν A [16]. There it has been shown that the sensitivity for the determination of mass hierarchy is above 2σ (i.e., $\chi^2 > 4$) only for δ_{CP} value around $\mp 90^\circ$ for true hierarchy and octant as NH-LO or HO-IH, where the scheduled run time, i.e., (3 yrs in ν mode + 0 yr in $\bar{\nu}$ mode) gives almost null sensitivity. The scheduled run period of NO ν A is for a total of six years with first three years in neutrino mode followed by the next three years in antineutrino mode. Therefore, it is of great importance to study the ability to discriminate the degeneracies between different oscillation parameters of this experiment within a minimal time-span, since it leads to an early understanding of neutrino oscillation parameter space. In this context, we investigate in this paper how to extract the best possible results from NO ν A with shortest time-span by analyzing its physics potential and degeneracy discrimination capability for a total of four years of runs, with two years in each neutrino and antineutrino modes. We have shown that the (2 + 2) years of run will provide much better sensitivity for the mass hierarchy determination in comparison to its scheduled run for four years i.e, 3 years in neutrino mode followed by one year in anti neutrino mode. Furthermore, we study the same by adding data from T2K experiment for a total of five years run with 3.5 years in neutrino mode and 1.5 years in antineutrino mode.

The outline of this paper is as follows. In section II, we present the details of simulation of T2K and NO ν A experiments that we have considered in this work. The neutrino oscillation parameter degeneracies are discussed in section section III. Section IV contains the discussion about the mass ordering and octant determination. Finally, we summarize our results in section V.

II. SIMULATION DETAILS

We simulate the neutrino oscillation events for T2K (Tokai-to Kamioka) as well as NO ν A experiments by using GLoBES package [17, 18]. T2K is also a currently running off-axis long-baseline experiment, which has been designed to study the phenomenon of neutrino oscillation. It uses an upgraded beam power of 0.77 MW and has the water cherenkov detector of mass 22.5 kton placed about 295 km away from Tokai. We simulate T2K experiment with updated experimental description as given in [22]. As we mentioned earlier, NO ν A experiment is an off-axis experiment with a baseline of 810 km, which uses a beam power of 0.7 MW and a detector of mass 14 kton. The experimental specifications of NO ν A are taken from [23] with the following characteristics:

Signal efficiency: 45% for ν_e and $\bar{\nu}_e$ signal; 100% ν_μ CC and $\bar{\nu}_\mu$ CC.

Background efficiency:

a) Mis-ID muons acceptance: 0.83% for ν_μ CC, 0.22% for $\bar{\nu}_\mu$ CC ;

b) NC background acceptance: 2% for ν_μ NC, 3% for $\bar{\nu}_\mu$ NC ;

c) Intrinsic beam contamination: 26% for ν_e , 18% for $\bar{\nu}_e$,

and we consider 5% uncertainty on signal normalization and 10% on background normalization. The migration matrices for NC background smearing are taken from [23]. The true values of oscillation parameters that we use in our simulation are listed in the Table-I [24].

$\sin^2 \theta_{12}$	0.32
Δm_{21}^2	$7.6 \times 10^{-5} \text{ eV}^2$
$\sin^2 2\theta_{13}$	0.1
Δm_{atm}^2	$2.4 \times 10^{-3} \text{ eV}^2$ for NH $-2.4 \times 10^{-3} \text{ eV}^2$ for IH
$\sin^2 \theta_{23}$	0.41 (LO), 0.59 (HO)
δ_{CP}	0°

TABLE I: The true values of oscillation parameters considered in the simulations taken from [24].

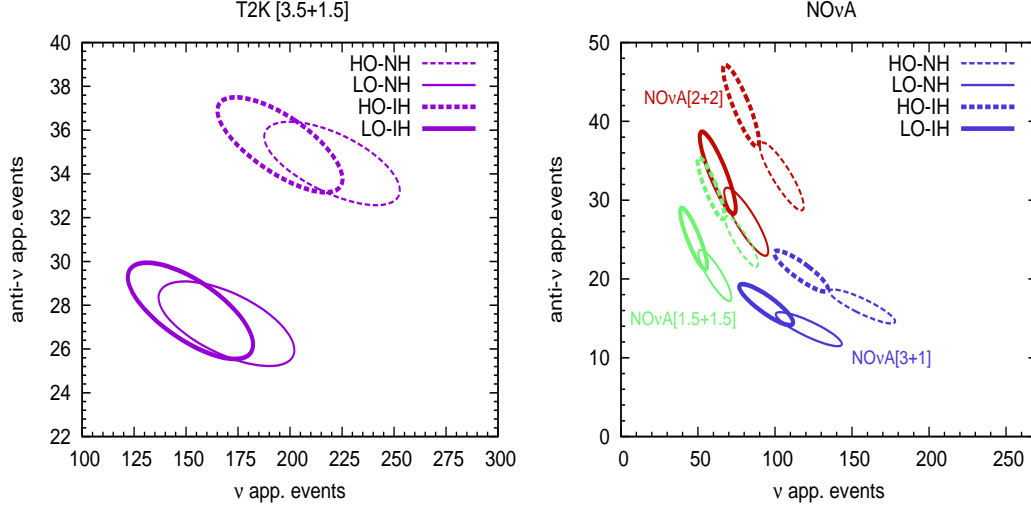


FIG. 1: Neutrino and antineutrino appearance events for the $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels by assuming both IH and NH and for lower and higher octants of θ_{23} .

III. NEUTRINO OSCILLATION PARAMETER DEGENERACIES

The parameter degeneracies in neutrino oscillation sector are of mainly three types and they are: $(\delta_{CP}, \theta_{13})$, sign of Δm_{31}^2 and $(\theta_{23}, \pi/2 - \theta_{23})$. Recently, the reactor experiments such as Daya Bay [25, 26], Double Chooz [27] and RENO [28] have precisely measured the value of the reactor angle as $\sin^2 2\theta_{13} \approx 0.089 \pm 0.01$. Therefore, the eight fold degeneracy is reduced to four-fold degeneracy. Out of these degeneracies, the degeneracy in which θ_{23} can't be distinguished from $(\pi/2 - \theta_{23})$ is called octant degeneracy and the degeneracy in the sign of Δm_{31}^2 is called hierarchy ambiguity. So far, we are left with four degeneracies and they are represented as NH-HO, NH-LO, IH-HO and IH-LO, where NH/IH (HO/LO) stands for Normal/Inverted ordering (Higher/Lower Octant). Resolution of these degeneracies are the main challenges of the present and future long-baseline neutrino oscillation experiments, which are mainly looking for oscillation from $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$. The expression for the oscillation probability, which is up to first order in $\sin \theta_{13}$ and $\alpha \equiv \Delta_{21}/\Delta_{31}$ is given as [29–31]

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\hat{A} - 1)\Delta}{(\hat{A} - 1)^2} + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \frac{\sin \hat{A}\Delta \sin(\hat{A} - 1)\Delta}{\hat{A}(\hat{A} - 1)} \cos(\Delta + \delta_{CP}), \quad (1)$$

where $\Delta = \Delta_{31}L/4E$ with $\Delta_{ij} = m_i^2 - m_j^2$ and $\hat{A} = 2\sqrt{2}G_F n_e E/\Delta_{31}$, where G_F is the Fermi coupling constant and n_e is the electron number density. For neutrinos, \hat{A} is positive for NH and negative for IH. For antineutrino, \hat{A} and δ_{CP} reverse their sign, i.e, $\hat{A} \rightarrow -\hat{A}$ and $\delta_{CP} \rightarrow -\delta_{CP}$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

The best way to express the degeneracies without any mathematical expression is simply by using bi-events curves. The bi-events plots for various octant-hierarchy combinations of T2K and NO ν A are depicted in Fig. 1, which are obtained by computing the $\nu(\bar{\nu})$ appearance events for the full range of δ_{CP} with a particular octant-hierarchy combination. From the plots, we can see that the ellipses for two hierarchies overlap with each other for both T2K and NO ν A for Lower Octant, which show that they have poor mass hierarchy discrimination capability. Whereas, the overlap is minimal for Higher Octant in the case of NO ν A, which shows that NO ν A has better degeneracy discrimination capability compared to T2K. However, the ellipses for HO and LO are very well separated and they have good octant resolution capability. Moreover, NO ν A (2+2) has better capability to determine the octant of θ_{23} among all other combinations due to balanced ν and $\bar{\nu}$ runs.

IV. MASS HIERARCHY AND OCTANT DETERMINATION

In this section, we obtain the potential of NO ν A experiment to determine the mass hierarchy and octant of atmospheric mixing angle and discuss the role of mass hierarchy-octant parameter degeneracy in the determination of these parameters.

A. Mass hierarchy determination

For the mass hierarchy determination, we obtain the sensitivity by calculating the χ^2 with which one can rule out the wrong hierarchy from the true hierarchy. We express this sensitivity as a function of true value of δ_{CP} , since it can be seen from Eq. (1) that there exists a degeneracy between hierarchy and δ_{CP} . Therefore, we simulate true events by taking NH (IH) as true hierarchy and test events by taking IH (NH) as test hierarchy for each true value of δ_{CP} . We obtain the χ^2 by using GLoBES and compare both event rates for full range of δ_{CP} . We do marginalization over all other parameters in order to get minimum χ^2 . We also add a prior on $\sin^2 2\theta_{13}$. We obtain this χ^2 for various true values of $\sin^2 \theta_{23}$ (i.e,

$\sin^2 \theta_{23} = 0.5$ for maximal mixing and $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO), since the octant of atmospheric mixing angle is unknown.

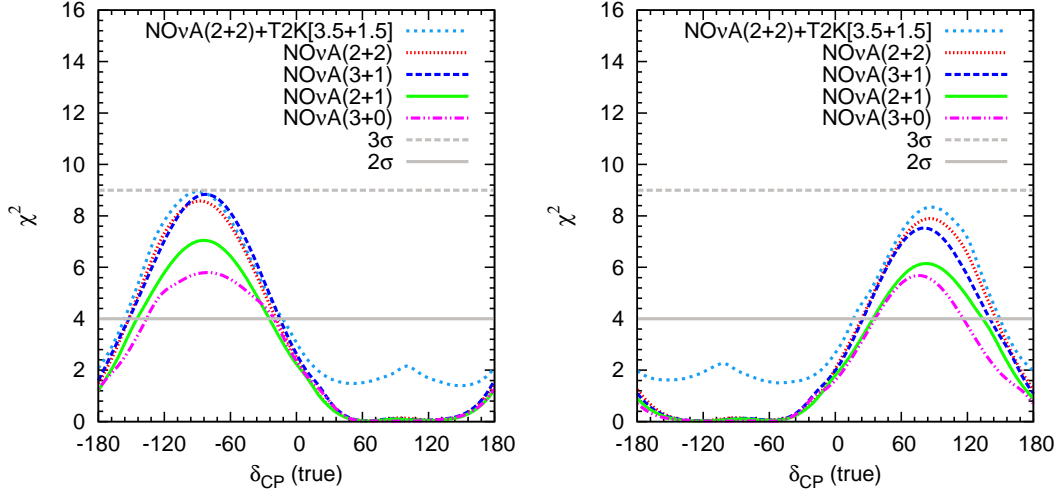


FIG. 2: The potential of determination of mass hierarchy. NH is considered as true hierarchy in the left panel and IH considered as true hierarchy in right panel.

In Fig. 2, we plot the value of χ^2 , obtained for maximal mixing of atmospheric angle, as a function of δ_{CP} . The left panel corresponds to true NH and the right panel is for true IH. From these figures, we can see that the potential to determine mass hierarchy for $\text{NO}\nu\text{A}$ is above 2σ for less than half of parameter space of δ_{CP} and it also depends on the neutrino mass ordering. The mass hierarchy sensitivity of $\text{NO}\nu\text{A}$ (2+2) is lower (higher) than that of $\text{NO}\nu\text{A}$ (3+1) for true NH (IH) and maximal mixing of atmospheric mixing angle. The sensitivity increases for a combined analysis of $\text{NO}\nu\text{A}$ (2+2) and T2K (3.5+1.5) and has a 3σ significance in the case of true NH. The mass hierarchy sensitivities for non-maximal atmospheric mixing angle are presented in Fig. 3. We consider all possible combinations with $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) for different combinations of neutrino and antineutrino run modes like $\text{NO}\nu\text{A}$ (2+1), $\text{NO}\nu\text{A}$ (2+2), $\text{NO}\nu\text{A}$ (3+0) and $\text{NO}\nu\text{A}$ (3+1). From these plots, we can see that the value of χ^2 is always above 6 for all cases of $\text{NO}\nu\text{A}$ (2+2), whereas for $\text{NO}\nu\text{A}$ (3+1) the χ^2 value is below 6 ($\sim 2.4\sigma$) for two combinations (NH-LO and IH-HO). Hence, $\text{NO}\nu\text{A}$ (2+2) has a good mass hierarchy discrimination capability compared to the scheduled run of $\text{NO}\nu\text{A}$ for four years. Thus, we can have an early information about the nature of mass ordering if $\text{NO}\nu\text{A}$ runs in $(2\nu + 2\bar{\nu})$ mode rather than its scheduled run of $(3\nu + 1\bar{\nu})$ years. Furthermore, if nature would be kind enough in the sense that the real

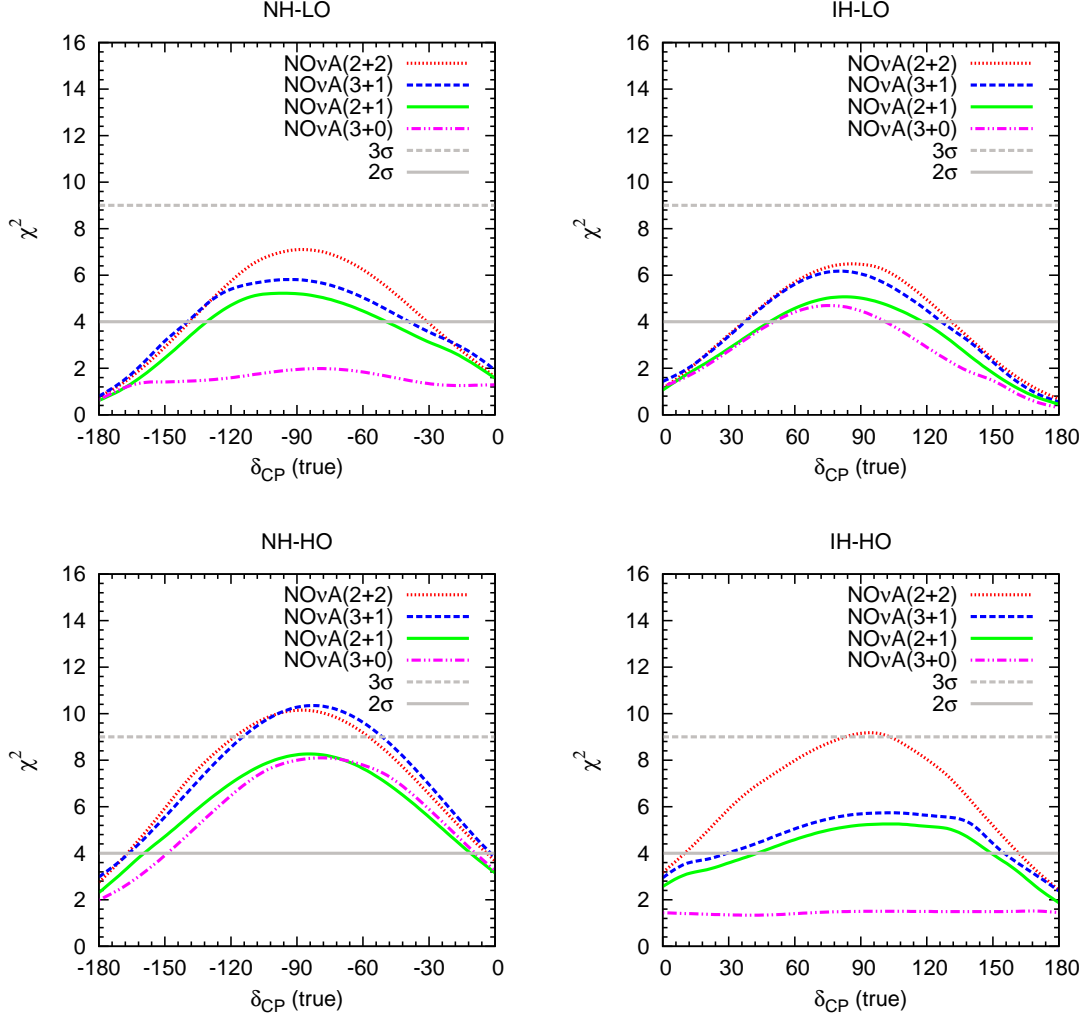


FIG. 3: The mass hierarchy sensitivities. The top (bottom) panel is for LO (HO), where we have used $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and left (right) panel is for true NH (IH).

mass ordering is inverted in nature and θ_{23} lies in the higher octant, then mass hierarchy can be determined with more than 2σ C.L. for values of δ_{CP} in the range $[0 : 180]^\circ$ with $(2\nu + 2\bar{\nu})$ years of run. Also if we compare the results of three years of run, the sensitivity for the determination of mass hierarchy is better for (2+1) combination than the scheduled (3+0) combination. This in turn implies that there would be better perspective if NO ν A runs in antineutrino mode after completing two years of run in neutrino mode.

B. Octant of θ_{23} determination

The hint of non-maximal atmospheric mixing angle observed by the MINOS Collaboration [11] is one of the recent subject of interest in neutrino oscillation sector. The deviation of θ_{23} from maximal ends up with two solutions so called lower octant ($\sin^2 \theta_{23} < 0.5$) and higher octant ($\sin^2 \theta_{23} > 0.5$). For the determination of resolution of octant of θ_{23} , we obtain the minimum χ^2 with which one can rule out the wrong octant from the true octant. Therefore, we simulate true events by taking LO (HO) as true octant and test events by taking HO (LO) as test octant. In order to obtain the χ^2 , we compare the true events and test events for true values of $\sin^2 \theta_{23}$ in the range $[0.32:0.68]$. We marginalize over other parameters $\sin^2 2\theta_{13}$, Δm_{31}^2 within their 3σ range and δ_{CP} in its full range. We also add a prior on $\sin^2 2\theta_{13}$.

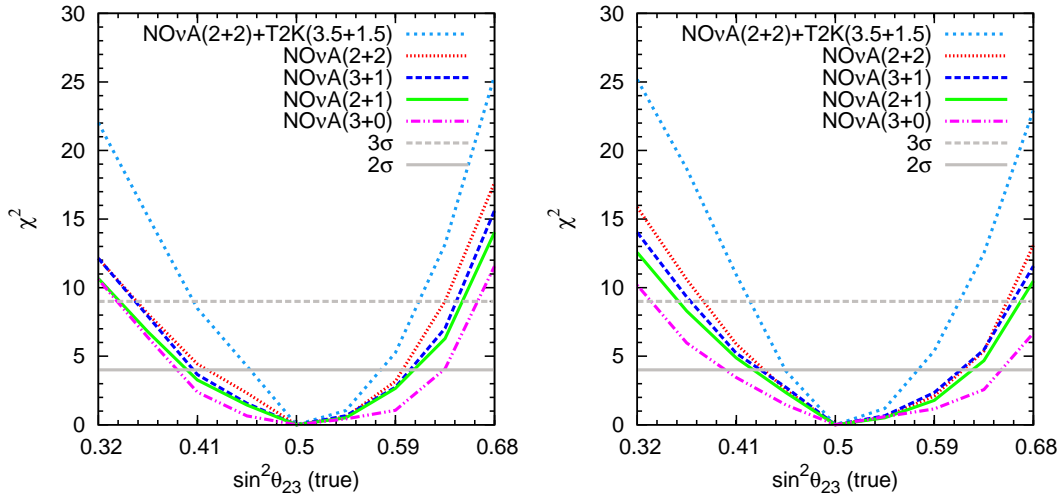


FIG. 4: The potential of octant resolution. NH is considered as true hierarchy in the left panel and IH considered as true hierarchy in right panel.

In Fig. 4, the obtained χ^2 is plotted as a function of $\sin^2 \theta_{23}$. Left panel corresponds to NH and the right panel corresponds to IH as true hierarchies. From the plots, it is clear that the potential to determine the octant of atmospheric angle is better for NO ν A (2+2), when compared with NO ν A (3+1). We can also see that a combined analysis of NO ν A (2+2) and T2K (3.5+1.5) has good octant resolution sensitivity.

C. Correlation between θ_{23} and Δm_{32}^2

The discovery reach of mass hierarchy and octant of atmospheric mixing angles are crucial because of the degeneracies between the oscillation parameters. Therefore, resolution of these degeneracies is very important to have a clear understanding of the neutrino mixing phenomenon.

In this section, we focus on the θ_{23} and Δm_{32}^2 degeneracy. First of all, we would like to see how does the hierarchy ambiguity affect $\sin^2 \theta_{23}$ - Δm_{32}^2 parameter space. Therefore, we simulate the true events for maximal value of $\sin^2 \theta_{23}$ ($\sin^2 \theta_{23} = 0.5$) and test events for allowed values of $\sin^2 \theta_{23}$ ($[0.32:0.68]$) and Δm_{32}^2 ($[2.05 : 2.75] \times 10^{-3} \text{ eV}^2$). We obtain the χ^2 by comparing true events and test events. We also do marginalization for both $\sin^2 2\theta_{13}$ and δ_{CP} and add a prior on $\sin^2 2\theta_{13}$. In Fig. 5, the obtained χ^2 is plotted as a function of $\sin^2 \theta_{23}$ and Δm_{32}^2 . From the plots, we can see that there is small difference in the allowed parameter space for NH and IH. However, there is no difference in the allowed parameter space for (2+2) and (3+1) years of NO ν A running as far as the determination of Δm_{32}^2 is concerned. We also get similar results when we compare the parameter space for both NO ν A (2+2) and NO ν A (3+1), and as expected such parameter spaces are significantly reduced when compared with NO ν A (2+1) and NO ν A (3+0). It should also be noted from the figure that the parameter space is substantially reduced for a combined analysis of T2K and NO ν A. Therefore, if we combine the (2+2) years of NO ν A results with (3.5+1.5) T2K results, the significance of the atmospheric mass square determination will improve significantly.

We also obtain $\sin^2 \theta_{23}$ - Δm_{32}^2 parameter space for non-maximal mixing of atmospheric mixing angle. We consider deviation from maximal mixing with $\sin^2 \theta_{23} = 0.41$ (0.59) for Lower Octant (Higher Octant). Fig 6 shows the $\sin^2 \theta_{23}$ - Δm_{32}^2 parameter space for NH-HO, NH-LO, IH-HO, IH-LO combinations. It is clear from the figures that, in this case also there is no significant difference between the allowed parameter space for (2+2) and (3+1) years of NO ν A run period. Therefore, the expected results on θ_{23} and Δm_{32}^2 degeneracy discrimination would not be deteriorated if NO ν A switches to antineutrino mode after completion of 2 years of neutrino run.

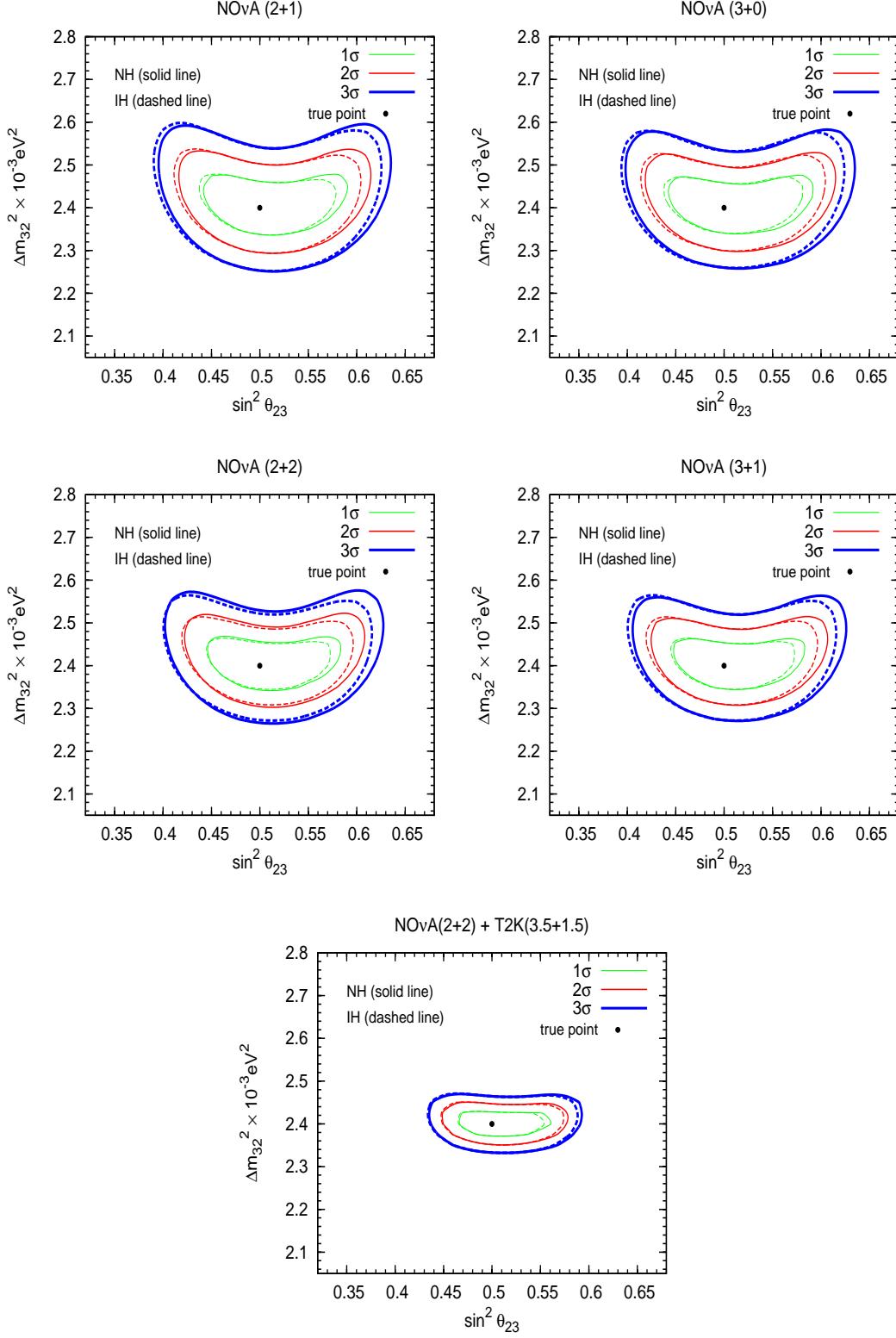


FIG. 5: The $\sin^2 \theta_{23} - \Delta m_{32}^2$ contour plots with true $\sin^2 \theta_{23} = 0.5$.

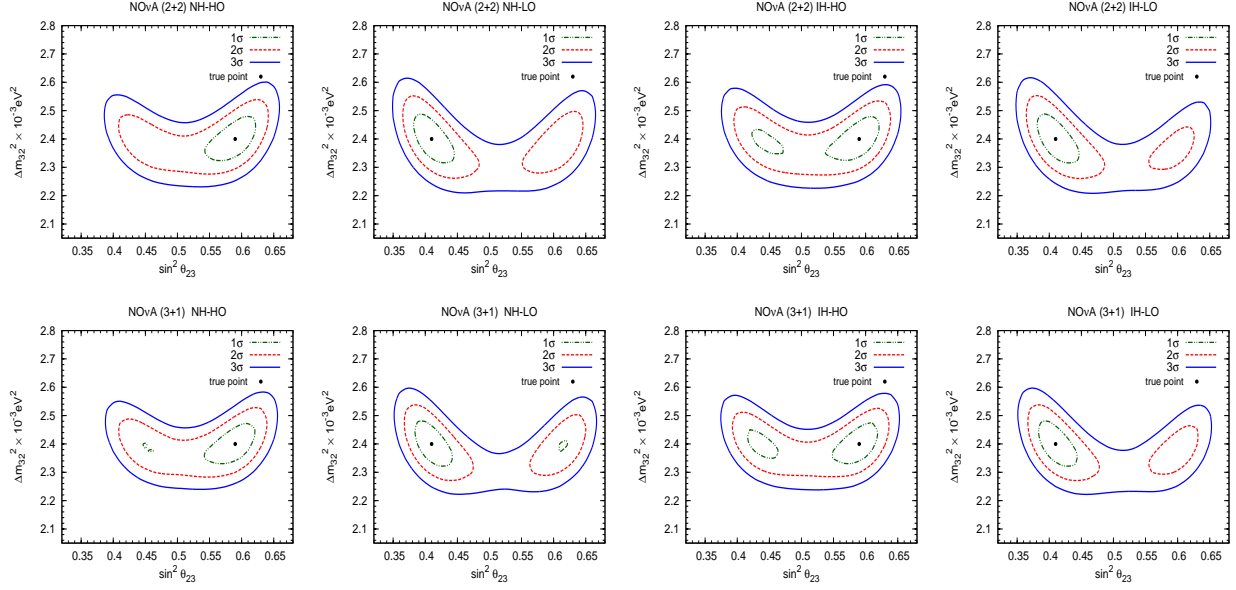


FIG. 6: The 1σ (green), 2σ (red), and 3σ (blue) C.L. regions for $\sin^2 \theta_{23}$ vs. Δm_{32}^2 with true $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and true $\delta_{CP} = 0$.

D. Correlation between δ_{CP} and $\sin^2 \theta_{23}$

Another way to understand the degeneracies among the oscillation parameters by looking at $\sin^2 \theta_{23} - \delta_{CP}$ plane. In this section, we show the 1σ , 2σ , and 90% C.L. regions for $\sin^2 \theta_{23}$ vs. δ_{CP} for both $\text{NO}\nu\text{A}(2+2)$ and $\text{NO}\nu\text{A}(3+1)$. Fig. 7 shows the C.L. regions for $\text{NO}\nu\text{A}$ with true $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and true $\delta_{CP} = 0$, whereas Fig. 8 corresponds to true $\delta_{CP} = \pi/2$. Further, the true hierarchy is assumed to be Normal Hierarchy and the C.L. regions are obtained both for correct hierarchy (NH-LO and NH-HO) and wrong hierarchy (IH-LO and IH-HO) combinations. The black dots in these figures correspond to the assumed true values. From these figures, we can see that $\text{NO}\nu\text{A}(2+2)$ has better degeneracy discrimination capability than that of $\text{NO}\nu\text{A}(3+1)$.

V. SUMMARY AND CONCLUSIONS

At this point of time, where $\text{NO}\nu\text{A}$ experiment already started taking data, it is crucial to analyze how to extract the best results from this experiment with shortest time span for a complete understanding of oscillation parameters. In this paper, we discussed the physics potential as well as the role of parameter degeneracies in the determination of oscillation

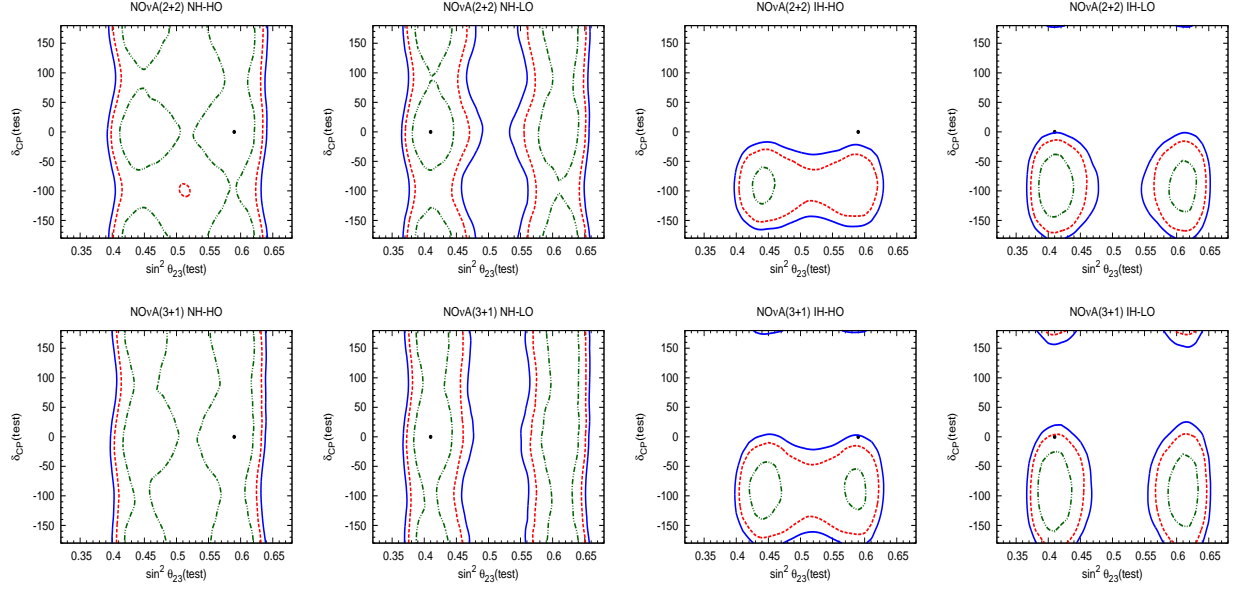


FIG. 7: The 1σ (green), 2σ (red), and 90% (blue) C.L. regions for $\sin^2\theta_{23}$ vs. δ_{CP} with true $\sin^2\theta_{23} = 0.41(0.59)$ for LO(HO) and true $\delta_{CP} = 0$.

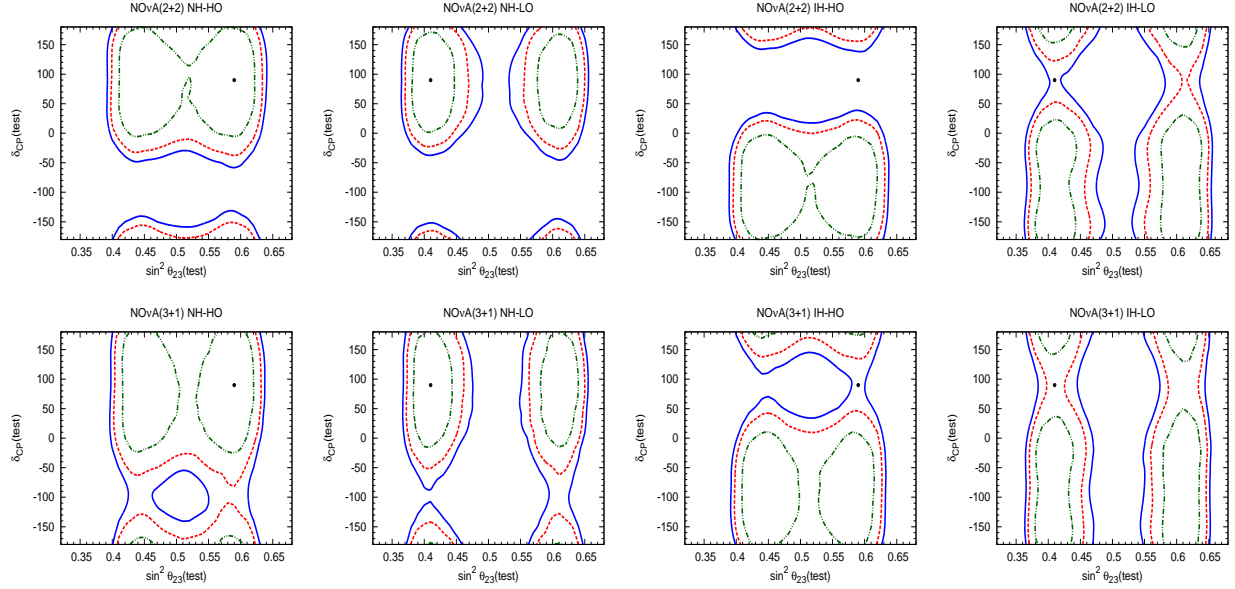


FIG. 8: The 1σ (green), 2σ (red), and 90% (blue) C.L. regions for $\sin^2\theta_{23}$ vs. δ_{CP} with true $\sin^2\theta_{23} = 0.41(0.59)$ for LO(HO) and true $\delta_{CP} = \pi/2$.

parameters of NO ν A experiment with a total of four years of runs with $(2\nu+2\bar{\nu})$ mode. We find that the parameter degeneracy discrimination capability of NO ν A (2+2) is quite good when compared with NO ν A (3+1). Looking all these results from our analysis, it is

strongly urged that after two years of neutrino running, NO ν A should run for two years in antineutrino mode to provide better information about the determination of neutrino mass ordering and the octant of atmospheric mixing angle.

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